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Daylighting metrics based on illuminance, distribution, glare and directivity

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A method is presented for assessing daylighting quality based on metrics related to illuminance, distribution, glare and directivity. The calculations are done using the programs RADIANCE and DAYSIM for a south-west and a north-west oriented offices in the CDP building in Montreal (latitude 45° 30′N). The results indicate that the following set of metrics is the most useful for assessing the daylighting quality of architectural spaces: Useful Daylight Illuminance (UDI), Daylight Glare Probability and Vector/Scalar illuminance ratio. The results also suggest that the daylight factor should be replaced by the UDI and that more empirical research is needed to establish appropriate criteria for acceptable luminance ratios in the case of well daylit buildings.

1. Introduction

Designing buildings that make a greater use of daylight and recognise the advantages of natural light could have great benefits for the occupants since solar radiation is naturally rich in the short wavelength (blue) radiation that regulates the circadian system.[1] It is recognised that daylight is generally preferred to electric lighting by occupants.[2–4] Also, daylight presence can significantly contribute to lighting quality in a space.[5] For example, glare studies have shown that glare is tolerated much more from a daylight source than from its electric equivalent.[6]

The exploitation of daylight, commonly referred to as 'daylighting', is also recognised as an effective means to reduce the electric lighting requirements of nondomestic buildings.[7–10] Besides direct savings, which reduce the energy consumption for lighting, indirect energy savings can be found because of the reduced heat production and hence the reduced energy consumption by air conditioning.[11]

Despite its multiple positive attributes, daylight is still a greatly underexploited natural resource[12] and not a high priority design aspect.[13] Reinhart[13] claimed that the indifference of many planners towards daylighting may be the result of a lack of informative daylight performance indicators and over-optimistic energy saving predictions that are rarely met in real buildings. In an attempt to overcome the first of these two limitations and contribute to the ongoing discussion about daylight metrics, this paper presents the results of a study where a methodology was developed to assess daylight quality in two office rooms of the Caisse de Dépôt et Placement (CDP), a large office building located in downtown Montreal, Canada.[14] The proposed methodology is based on the computation of various indicators or so-called 'daylight metrics' related to illuminance, distribution, glare and directivity based on an earlier publication about daylight quality.[15]

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2. Background

2.1. Traditional approaches

The literature on architecture and engineering has traditionally focused on only one parameter to evaluate lighting conditions: The horizontal illuminance.[16] Controlled studies as well as anecdotal evidence indicate that it is not only the illuminance on the working plane that is important; many other aspects of the lighting throughout the whole visual space, such as the spectral distribution, luminance and illuminance uniformity, temporal variation in illuminance, etc., must also be considered.[17] A simple consideration of horizontal illuminance at work plane height is a serious limitation and does not represent a complete methodology for the assessment of lighting conditions.[16,18] Non-horizontal components of lighting need to be considered as well because these are the components perceived by the occupants.[16]

Apart from the fact that architects and researchers often use a limited range of parameters to assess lighting quality, the methodologies used contain important limitations. For example, the daylight factor (DF), another widely used indicator, is clearly insufficient due to its intrinsic limitations:[19,20]

- Light from the sun and non-overcast skies cannot be considered with the DF.
- The DF does not allow an evaluation of the impact of building/room orientation.
- DF values are very variable even under overcast sky conditions due to variable sky luminance distributions.
- The effect of mixed lighting (natural and electric) cannot be quantified with the DF.
- The non-horizontal lighting of the walls, which is critical for human perception, is not considered in the measurement of the (horizontal) DF.

The DF only applies to a temperate climate with many cloudy situations[3] but according to some authors[21] the actual daylight illumination conditions deviate markedly from the overcast sky paradigm, even for Northern Europe where there is a commonly held belief that skies are 'mostly' overcast. Daylight is inherently climate-dependent and time-varying and the DF takes no account of this everyday reality.[12]

The problem thus appears clearly, researchers must explore new indicators of performance.[18] Moreover, recent developments in lighting simulation techniques offer new opportunities to optimise the evaluation work of the researcher by taking into consideration a variety of indicators of daylighting quality.

2.2. New 'daylight metrics'

The European Standard EN 12464-1[22] states that the main parameters determining the luminous environment are:

1) luminance distribution;
2) illuminance;
3) glare;
4) directionality of light;
5) colour rendering and colour appearance of the light;
6) flicker;
7) daylight.

These parameters are also listed in a previous multi-author book[15] except for the last three parameters (colour, flicker and daylight). This earlier book[15] listed illuminance, distribution, glare and directivity as important parameters of daylighting quality:

Illuminance Generally a good visibility is defined by the presence of an adequate amount of light allowing the occupant to accomplish his tasks.

Distribution A uniform distribution of illuminance and luminance is required.

Glare The absence of glare is a necessity.

Directivity The directivity of light allows objects in space to be distinguished.

For a well-daylit building, this list of parameters is sufficient since colour rendering and colour appearance of the light will be similar to daylight unless the glazing colour is strongly distorted. Also, flicker and daylight need not to be considered in well-daylit buildings. Thus, in this study, an evaluation based on illuminance, distribution, glare and directivity[15] was judged the most adequate and yet sufficiently detailed to assess daylight quality in the offices under study.

At the same time as this study was initiated, key research on photobiology[23] was published, research which made it possible to establish relationships between spectral light characteristics and the photobiological response in humans. Following the dissemination of these findings, many researchers have incorporated so-called photobiological aspects into their lighting quality models. For example, a new model called the VBE model for Visual, Biological and Emotional has recently been proposed by Swedish researchers.[24] The VBE model was unfortunately still under development when our study was carried out and precise benchmarks for evaluating adequate photobiological lighting quality in terms of intensity and time of exposure were critically lacking when we were performing our simulations.

3. Method

3.1. Metrics used

Table 1 presents some of the metrics and criteria used to assess daylighting quality in

Table 1 Metrics used to assess daylight quality in the offices of the CDP

Daylight parameter	Metric	Criteria	Source
Illuminance	DF	*DF 5% or more*: The room has a bright daylit appearance. Daytime electric lighting is usually unnecessary. High levels of daylight may be associated with thermal/ glare problems. *DF 2–5%*: The room has a daylit appearance but electric light is usually necessary in working interiors. *DF below 2%*: Electric lighting is necessary and appears dominant.	Trezenga and Loe[25]
	UDI	Calculated for illuminances between 100 lx and 1000 lx and between 100 lx and 2000 lx: $<$100 lx = falls short of the useful range $>$2000 lx = exceeds the useful range	Nabil and Mardaljevic[20]
Distribution	Luminance ratios in field of view	*1:3:10* The luminance in a cone of 60° about the line of sight should not exceed three times or be less than one third of the luminance of the main visual task. The luminance in a cone of 120° should not exceed 10 times or be less than a tenth of the luminance of the main visual task.	NUTEK[26] Van Ooyen *et al.*[27] IESNA[28] CIBSE[29] Dubois[30]
Glare	DGP	A low value indicates a low probability for discomfort glare.	Wienold and Christoffersen[31,32]
Directivity	Ratio of vector to scalar illuminance (Ev/Es)	Preferred value in the range 1.2–1.8 in a scale of 0–4.	Cuttle[33]
	Altitude of illuminance vector	Ideal between 15° and 45°.	Cuttle[33]

The complete set of metrics is presented in Cantin.[14]

the offices of the CDP. Detailed justifications for each metric and criteria are provided elsewhere.[14] This list of metrics is not exhaustive. Since this study was terminated, new indicators have been proposed. For example, a metric called Daylight Autonomy (DA) has been developed.[13] The DA is defined as the percentage of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight.[34] In later publications, the concept of DA was further refined by combining it with a manual blind control model that predicts the status of movable shading devices at all time steps in the year. The resulting concept of 'effective' DA has been applied to open plan and private offices.[13,35]

Recently, an indicator called Continuous Daylight Autonomy (DA_{con}) has been proposed.[36] In contrast to earlier definitions of DA, partial credit is attributed to time steps when the daylight illuminance lies below the minimum illuminance. For example, in the case where 500 lx is required and 400 lx is provided by daylight at a given time step, a partial credit of $400/500 = 0.8$ is given for that time step. This metric acknowledges that even a partial contribution of daylight to illuminate a space is still beneficial.[36]

3.2. Light simulation programs used

This study was entirely carried out by simulation using the RADIANCE Lighting Simulation System[37] and DAYSIM.[38] RADIANCE has been used in many previous studies and validated.[39–44] DAYSIM is a RADIANCE-based daylighting analysis tool developed at the National Research Council of Canada and the Fraunhofer Institute for Solar Energy Systems in Germany. DAYSIM uses the daylight coefficient method to efficiently calculate illuminance distributions under all sky conditions in a year[38] and the Perez sky model.[45]

3.3. Description of the computer model

3.3.1. Geometry of the offices

Two offices located on the fifth floor of the CDP were selected for the study. One office (SW) was located on the South West facade while the other office (NW) had a North West orientation. The offices, furniture and curtain wall were modelled in detail (Figure 1). Information concerning the optical properties of the surfaces, the modelling of neighbouring buildings and the general indoor environment can be found elsewhere.[14] The offices were modelled with the electric lights turned off and no shading devices were assumed, which is unrealistic but one goal of the study was to determine if shading devices were needed and what properties these should have. Besides computer simulations, light measurements as well as questionnaire interviews with occupants of the space were carried out. However, it has not been possible to have access to this data due to technical and time constraints. This paper therefore focuses on the computer simulations done as part of this research project.

3.3.2. Simulation times

Simulations were performed for a limited number of clear skies, one standard CIE overcast sky and Perez skies in DAYSIM. For the clear sky simulations, a series of small fish-eye views from the ceiling of each office – looking downwards – were generated making it possible to quickly identify the situations for which direct sunlight was penetrating the room (Figure 2). The situations for which no direct sunlight was penetrating the room and symmetrical situations with respect to the solar position were eliminated. As a result of this analysis, a total of 37 and 15 clear skies were selected in the SW and NW offices, respectively.[14]

Figure 1 Fish-eye views showing the digital models of the SW (left) and the NW (right) offices

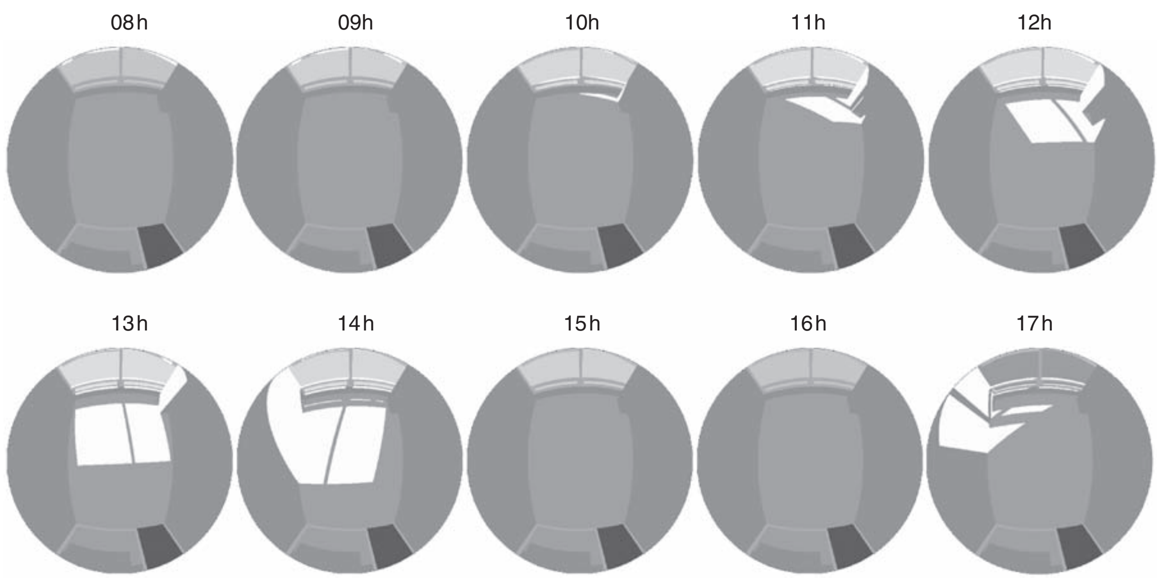

Figure 2 Preliminary study showing fish-eye views of the SW office seen from a central point on the ceiling looking down, for the 21 August and all times of the day

3.4. Data collection and analysis

3.4.1. Useful daylight illuminance

For the calculation of the UDI, grids of sensors were defined in DAYSIM for the whole room as well as for the working plane.[14] The UDI was calculated for two illuminance ranges: 100–1000 lx and 100–2000 lx. Initially, the UDI was compiled for the range 100–2000 lx based on previous empirical evidence.[46,47] The 2000 lx level was considered a bit high due to the fact that many lighting standards set illuminances below 500 lx in rooms where computer work is performed. For example, the CIBSE Code for Interior Lighting[29] recommends maintaining the illuminance on the horizontal work plane of rooms where VDTs are used extensively in the range 300–500 lx as far as practicable; illuminances towards the lower end of this range are appropriate where the task is wholly, or substantially screen-based. Many studies indicate a need for lower illuminances with computer work.[48,49] After our study was terminated, it was suggested that the UDI scheme could be enhanced by dividing the UDI 100–2000 lx range into two; a 100–500 lx range and a 500–2000 lx range.[12]

3.4.2. Luminance ratios

In each office, the luminance ratios were calculated for an occupant sitting at the computer and paper tasks. The program *pvalue* in RADIANCE was used to obtain the luminance values of each pixel of the fish-eye image corresponding to the direction of gaze. These data were then analysed with a spreadsheet for 60° and 120° cones about the line of sight. The luminance ratios analysis also required the calculation of the luminance of the paper and computer tasks for every case. In order to simplify data analysis, task luminance values were determined indirectly using a methodology developed earlier:[30]

- The background of the computer screen was white with black text, and had a luminance of 90 cd/m^2;
- The paper task consisted of a perfectly diffuse, white sheet of paper with a reflectance of 80%. The luminance was calculated from the illuminance using Lambert's law.

3.4.3. Glare

The Daylight Glare Probability (DGP)[31,32] was used in this study since a good correlation between the occupants' perception and the DGP has been demonstrated. Also, this index was easy to calculate using the program *Evalglare*[50] which uses fish-eye images generated by RADIANCE. The DGP was assessed for two main orientations of visual field (Figure 3), namely for an occupant facing his computer and for an occupant facing the desk adjacent to the computer screen (paper task).

3.4.4. Directivity: Scale of shadow and *Ev/Es* ratio

Most of lighting quality metrics presented so far are two-dimensional in nature. The use of two-dimensional metrics for the assessment of lighting quality does not adequately convey the intrinsic three-dimensional nature of lighting.[19,33] Some years ago, a Danish professor[51,52] proposed a methodology for assessing the three-dimensional modelling of lighting. He named his system 'The Scale of Shadows'. This system allows a classification of lighting directivity based on the observation of shadow patterns on white diffuse spheres. Despite its interest for the analysis of light modelling, the Scale of Shadows proved difficult to apply in practice, especially for situations with more than one light source, because it is based on subjective observations of a number of spheres.[53] For a rating system, it is often more desirable to come up with a single metric for a space.[34]

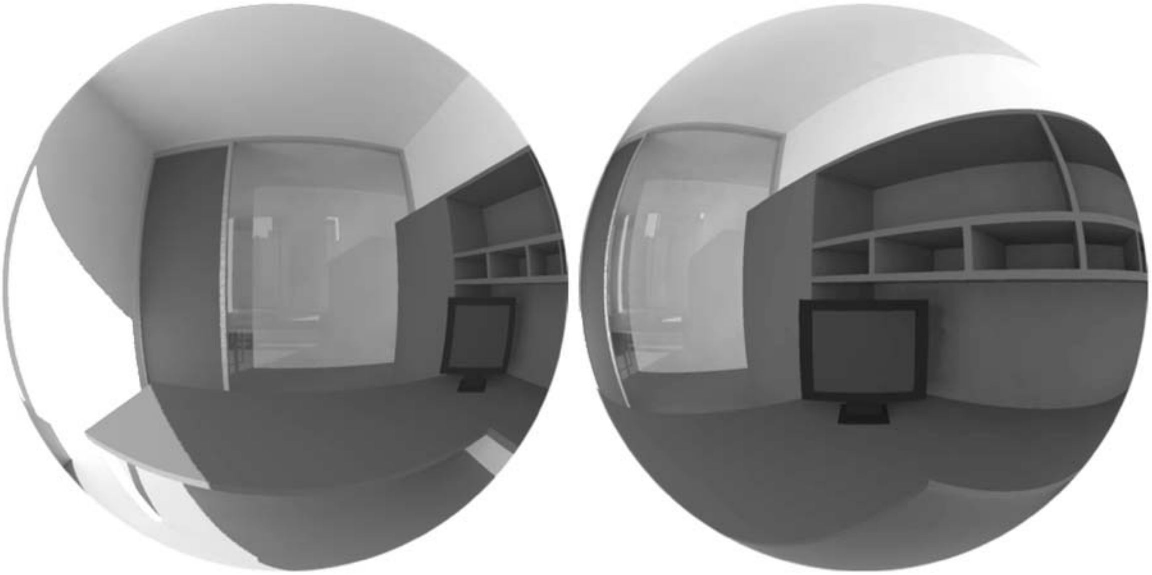

Figure 3 Visual fields considered for the study of DGP in the SW office (writing and reading/meeting tasks to the left and computer tasks to the right)

Cuttle[33] provided a solution to this problem by introducing a single indicator called the vector-to-scalar illuminance ratio (Ev/Es) to evaluate the three-dimensional appearance of objects in space. In this ratio, the vector illuminance (Ev) is obtained by adding all illuminance vectors incident on a sphere placed at a particular point of interest while the scalar illuminance (Es) is defined as the average illuminance on the sphere. The Ev/Es ratio always results in a value between 0 and 4 due to geometrical considerations. This model was tested by studying preferences of people for the appearance of human faces in an interview situation and it was determined that an Ev/Es ratio between 1.2 and 1.8 was generally preferred. A scale for interpreting the Ev/Es ratio was also proposed (Table 1). In addition, Cuttle[33] mentioned that people preferred a more lateral orientation than a more vertical orientation for this so-called 'flow' of light. The study showed that a light vector with an altitude between 15° and 45° was preferred by the majority of people.

In our study, the analysis of directivity was achieved by computing the Ev/Es ratio and by rendering spheres in the offices for a visual analysis of the light situation only when needed. These renderings used four spheres with a radius of 0.15 m, corresponding approximately to the size of a human head, with the centre located at 1.25 m from the floor (Figure 4). These positions allowed an evaluation of daylight quality at strategic positions:

- Sphere 1 provided an evaluation in the area close to the window;
- Sphere 2 corresponded to the position of the office worker;
- Sphere 3 allowed an evaluation above the writing and reading desk;
- Sphere 4 was placed in the area where the head of a visitor is normally placed.

4. Results

This paper only presents the most interesting results of the study. The reader is encouraged

Figure 4 Example of a section view for the SW office with the four spheres for the analysis of directivity (Dec. 21, 13 hours, clear sky)

to read the original thesis for a complete report of the simulation results.[14]

4.1. Illuminance

4.1.1. Daylight factor

The simulations performed with the program *Dayfact* in Radiance allowed us to calculate the distributions of DF at 0.75 m above the floor (Figure 5). In this paper, the Tukey boxplots show the minima (bottom horizontal line), lower quartile (bottom of box), median (thick horizontal line in the box), upper quartile (top of box) and maxima obtained (top horizontal line). Outliers, which were arbitrarily defined as values smaller or larger than 1.5 times the interquartile interval, are presented as small circles below or above the minima or maxima (Figures 6, 8 and 9).

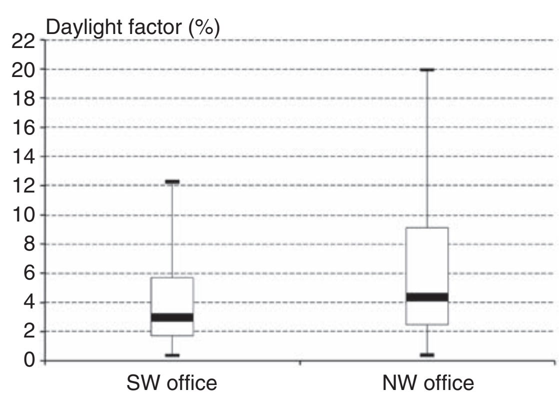

Figure 5 Distribution of DFs obtained at 0.75 m from the floor under overcast skies

For the NW office, an average DF of 5.8% was obtained while the SW office had an average DF of 4.1%. The SW office had an acceptable illuminance according to the criteria of Table 1 while the NW office, with an average DF higher than 5%, allowed DA, with a risk for glare in approximately half of the room. The DF was also calculated on the paper and computer tasks. The results (Table 2) show that the NW office provided more light on both surfaces. The higher DF values obtained for the NW office are due to the larger (corner) fenestration combined with a highly reflecting facing building facade (Figure 1).

4.1.2. Useful daylight illuminance

Tables 3 and 4 present the results obtained for the UDI for two illuminance ranges (100–1000 lx and 100–2000 lx). Table 3 indicates that in the NW office, the UDI was reached more often than in the SW office. However, both offices obtain relatively low results for UDI reached (whole office: 40.3% in NW office; 34.1% in SW office). The SW office obtained values that exceeded 2000 lx 63.5% of the time, which means that most of the time, there was too much daylight in the space. The NW office performed slightly better with 57.3% of UDI exceeded but in both cases, the results indicate too much daylight in the space, with risks for glare.

The analysis of illuminance on the computer task shows satisfactory results for the 100–2000 lx range and the performance of the NW office is slightly superior with 93.6% of the values within the acceptable range. The performance is not as good for the paper task where only 50.9% and 53.5% of the values are within the 100–2000 lx range and 2000 lx is exceeded for 45.5% and 43.4% of the time in the SW and NW offices, respectively. Globally, the UDI indicates that the NW office has a superior performance in terms of illuminance compared to the SW office.

Table 4 presents the results obtained for the 100–1000 lx range. For this range, the UDI is reached about half as often compared to the 100–2000 lx range. The results show that the performance of both offices is weak with respect to this range with UDI reached for only 17.6% and 19.6% of the times in the SW and NW offices, respectively. The UDI was exceeded the majority of the time, confirming that there is a risk for glare in the offices.

Table 2 Average DF (%) for work surfaces in SW and NW offices

	Paper task	Computer task
SW office	2.5	1.8
NW office	4.0	2.9

Table 3 UDIs obtained for the SW and NW offices, for the illuminance range 100–2000 lx

	SW office		NW office	
Whole office	34.1	**63.5** *2.5*	40.3	**57.3** *2.4*
Paper task	50.9	**45.5** *3.6*	53.5	**43.4** *3.2*
Computer task	82.9	**11.9** *5.3*	93.6	**0.02** *6.4*

Percentage UDI reached are shown in normal format; percentage UDI exceeded in bold; percentage UDI falling short in italics.

4.2. Distribution

4.2.1. Luminance ratios, sunny skies

Figure 6 summarises the results obtained regarding luminance ratios calculated for sunny skies. It shows that the luminous

Table 4 UDIs obtained for the SW and NW offices, for the illuminance range 100–1000 lx

	SW office		NW office	
Whole office	17.6	**79.9** *2.5*	19.6	**78.0** *2.4*
Paper task	25.6	**70.8** *3.6*	26.2	**70.6** *3.2*
Computer task	39.7	**55.0** *5.3*	53.7	**39.8** *6.4*

Percentage UDI reached are shown in normal format; percentage UDI exceeded in bold; percentage UDI falling short in italics.

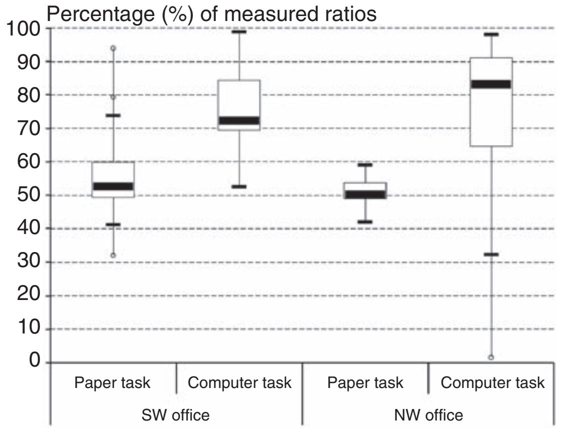

Figure 6 Percentage distribution of acceptable luminance ratios, for the SW and NW offices, sunny skies, for paper and computer tasks

Table 5 Comparison of luminance ratios for the SW and NW offices under overcast skies

	SW office		NW office	
Paper task	55.37	**44.63** *0.00*	56.46	**43.54** *0.00*
Computer task	8.32	**91.68** *0.00*	24.87	**75.13** *0.00*

Percentage of acceptable luminance ratios are shown in normal format; percentage of luminance ratios corresponding to a task which is too bright in bold; percentage of luminance ratios corresponding to a task which is too dark in italics.

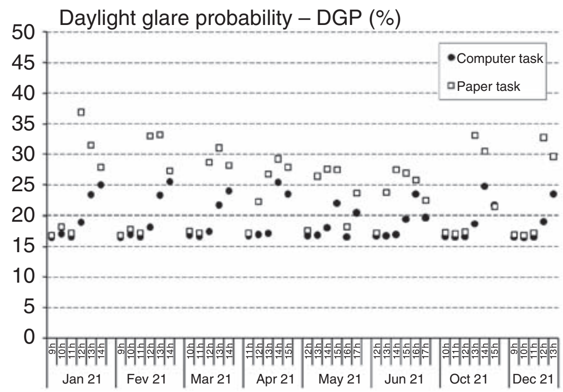

Figure 7 DGPs obtained for the SW office under sunny skies for the computer and paper tasks. For each day, data is given for each hour between 09.00 and 14.00 hours

conditions in both offices are similar but that the SW office provides a slightly better performance in terms of luminance ratios for paper tasks than the NW office. On the other hand, the NW office obtained slightly higher numbers of acceptable ratios in the area of the computer task. Thus, under sunny skies, both offices present luminance conditions that are generally adequate for computer work while showing some limitations (about 50% of the ratios inadequate) for paper work.

4.2.2. Luminance ratios, overcast skies

Table 5 presents the percentage of acceptable luminance ratios under overcast sky conditions, showing that the offices offer similar performance in terms of luminance ratios for paper tasks and that this performance is weak. For computer tasks, both offices have a very weak performance. Table 5 also shows that most of the unacceptable ratios correspond to situations for which the task is too bright with respect to surrounding surfaces. This weak performance is caused by the dark furniture (reflectance = 0.10). A higher reflectance for the furniture could have reduced the contrast between the task and the surrounding surfaces. The furniture should ideally have a reflectance value between 0.25 and 0.45.[54]

4.3. Glare

4.3.1. Daylight glare probability

The results obtained for the DGP under sunny skies are presented in Figure 7 for the SW office. Figure 7 shows that, generally, the DGP is lower for the computer task. The computer task area does not receive any direct sunlight patch, which greatly reduces the occurrence of glare problems. The majority of DGP values obtained for the computer task (31/45) are below 20%. Below 20%, the risk for glare is negligible.[31,32] Moreover, the calculation did not return any DGP greater than 26%. Thus, it can be concluded that the SW office performs well regarding DGP, under sunny skies for the computer task. The results are not as outstanding for the paper task where about half of the calculated DGP values (22/45) were above 25% probability for glare. Note that high DGPs (Jan. and Feb. 21 at 12 hours and 13 hours) correspond to situations for which there was a direct sunlight patch on the desk top. In spite of these observations, the SW office offers an acceptable performance regarding glare according to calculated DGP values, since the maximum DGP is around 37% (Jan. 21, 12 hours).

The results for NW office returned higher DGP values for the computer task compared to the paper task.[14] This difference is due to the fact that the computer screen in the NW office was placed such that the occupant had a reflected view of the sky, which significantly increased the risk for glare (Figure 1).

4.4. Directivity

4.4.1. Ev/Es ratios and vector altitudes

Figure 8 presents a synthesis of the results obtained for the Ev/Es ratios in the SW and NW offices, under sunny skies. In the SW office, sphere 4 obtained the 'best' results since the majority of Ev/Es ratios were between 1.2 and 1.8. This sphere did not receive direct sunlight and this yielded more acceptable ratios, according to the criteria defined in Table 1. For the three other spheres, Figure 8 shows that, generally, the Ev/Es ratios were above the recommended values, with median values ranging from 2.1 (moderately strong) to 2.6 (strong directivity). Sphere 1 had the highest ratio indicating that light was more directional on this sphere, which is an expected result since this sphere was located close to the window.

In the NW office, the results for the Ev/Es ratios under sunny skies show that the majority of the calculated ratios were above the recommended values. Sphere 1 (close to the window) was the one with the highest values and the ratios were also more varied for this sphere with about a fourth of the ratios between 2.6 and 3.0, which is associated with strong to very strong directivity. Sphere 2 obtained the 'best' results with average and median ratio values around 2.1, thus moderately strong directivity and pleasant appearance. Despite the fact that the majority of calculated ratios for the NW office exceeded the recommended limit, the average value was around 2.1, which corresponds to moderately strong to strong directivity according to Table 1.

In general, the directivity across the depth of the room was more constant in the NW office. This is due to the fact that the SW office received more direct sunlight in the periphery of the window, creating more variability in the space. Also, the NW office had a facing reflecting building facade, which sent a dominant, near-horizontal light vector into the space, thereby contributing to more even

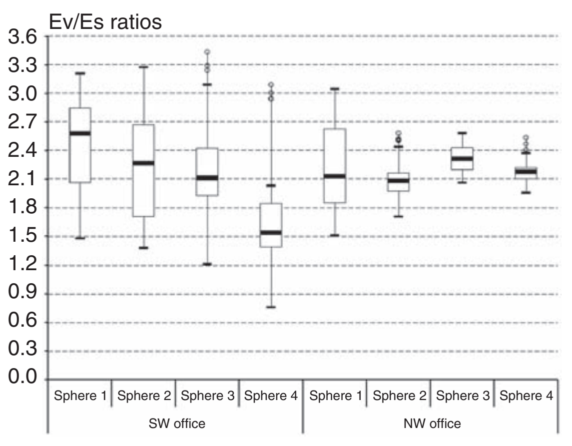

Figure 8 Distribution of vector/scalar illuminance ratios obtained for the four spheres in the SW and NW offices, under sunny skies

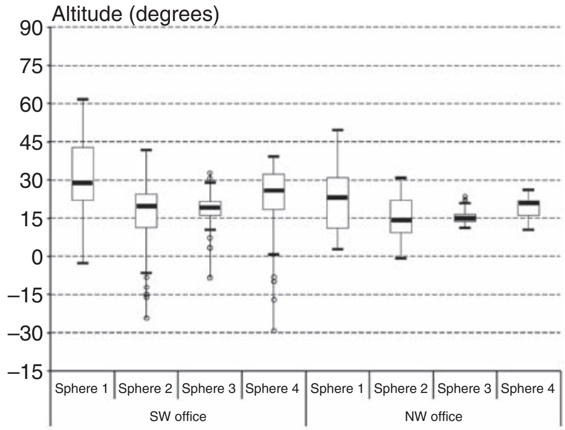

Figure 9 Distribution of altitude vector directions obtained for the four spheres in the SW and NW offices, under sunny skies

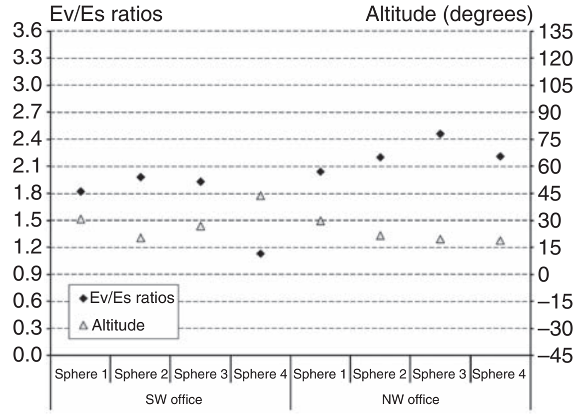

Figure 10 Vector/scalar illuminance ratios (Ev/Es) and altitude vector directions obtained for the four spheres in the SW and NW offices under overcast skies

lighting conditions across the depth of the room.

Figure 9 presents the altitude vectors obtained in the SW and NW offices under sunny skies. The figure shows that the majority of the ratios were within the set limits for the SW office. Sphere 3 obtained 'better' results with no ratio above 45° and few under 15°. Sphere 4 obtained similar results but a larger number of negative altitudes were obtained. Negative altitudes are caused by light reflected from the floor to the lower portion of the sphere. The calculations for the NW office revealed a greater stability for altitude vectors. The altitude vectors were also slightly lower in this office compared to the SW office, which is an expected result since the NW office received more light reflected from the facing building facade.

Figure 10 presents the Ev/Es ratios as well as altitude vectors for the SW and NW offices under overcast skies. Figure 10 shows that the altitude vectors fall within the recommended criteria for all spheres in both offices. However, for the Ev/Es ratios, three out of four spheres in the SW office produced slightly too high ratios with respect to the recommended criteria, indicating slightly too much directivity. On the other hand, the ratio of sphere 4 at the back of the room was too low, indicating a weak directivity. Figure 10 also shows that the Ev/Es ratios obtained in the NW office were also too high with respect to the recommended criteria, for the four spheres. In this office, the light reflected from the facade facing the building increased the directivity of daylight on sphere 4. The ratios in the NW office were also generally higher than in the SW office, which could be due to differences in the immediately surrounding context: Reflecting building facade in front of NW office, higher portion of horizon blocked by facing building, larger corner fenestration.

5. Discussion

A method for assessing daylight quality in office rooms based on a series of daylight metrics related to illuminance, distribution, glare and directivity is presented. The method is then used to assess daylighting quality in two office rooms located on the SW and NW facades of the CDP office building in Montreal, Canada. The daylight metrics are calculated using computer simulations with RADIANCE and DAYSIM. The assessment allows us to characterise and compare daylighting quality in the two rooms and arrive at the following conclusions.

5.1. Conclusions

In terms of illuminance, the DFs obtained indicated that both offices were sufficiently daylit. The NW office generally received more daylight than the SW office under overcast conditions due to the larger (corner) fenestration. A study of UDI indicated that there was even a risk for overlighting and glare in both rooms. This risk was generally slightly higher in the SW office and for paper tasks, according to the UDI values calculated. The UDI thus confirms that visual protection devices are needed in both rooms, even in the NW room, which received substantial reflected light from a facing building facade and which had a larger window area.

In terms of luminance distribution, the results indicated that both offices had a similar performance regarding luminance ratios under sunny skies. Many ratios were not acceptable with the task being too bright with respect to surrounding areas. This was caused by the very dark furniture selected by the architect. The study of luminance ratios was thus informative and provided quantitative proof that these offices should have furniture with a lighter surface colour. A method for analysing the luminance ratios inspired by the UDI (i.e. ratios acceptable, task too bright and task too dark) was proposed and could be established as a standard way of reporting luminance distribution results in future studies.

Regarding glare, the majority of DGP values obtained for the computer task (31/45) were below 20%, which indicated a low probability of glare. For the paper tasks, the results indicated a moderate risk for glare under sunny skies in the afternoon in the SW office. In this case, the high DGPs occurred in the afternoon, when the office received direct sunlight in the task area. In the NW office, the risk of glare was also higher at the end of the day and higher for the computer task due to a direct view of the sky from the computer task. These results confirm the fact that visual protection devices are needed in direct sunlight at the end of the day.

In general, the low DGP values obtained were quite surprising, especially given the weak performance regarding luminance ratios. The DGP values are more sensitive to the presence of direct sunlight than subtle luminance contrasts under diffuse lighting. We expected the DGP values to be higher since many luminance ratios were not acceptable according to the set criteria. However, this may be due to the fact that tolerance for larger contrasts in luminance is higher with daylight. The commonly cited rule of thumb of luminance ratios of 1:3:10 has been questioned recently since it is based on studies with very few subjects.[55] Also, Sutter *et al*.[56] observed that ratios of 1:6:20 were acceptable when a window was present in the visual field. In their experiment, a tolerance for a ratio of 1:50 has even been observed when the luminance from the window occupied a small portion of the visual field (about 5%). The lack of concordance between the luminance ratios and DGP analysis in this study confirms that more empirical research is needed to confirm the acceptable luminance ratios in well-daylit rooms.

Regarding directivity, our study showed that the method proposed by Cuttle is very useful to characterise the directivity of light in the space and provides additional information, which is not provided by the other metrics studied. In this case, the Ev/Es ratios obtained were more variable in the SW office compared to the NW office, which was due to the direct sunlight patch in the SW office, creating more variability in directivity. The Ev/Es ratios were generally more stable in the NW office across the depth of the room, probably due to the facing building facade, which sent a near-horizontal light vector along the depth of the NW office. The study generally showed Ev/Es ratios above the set criteria, indicating too high directivity, which is obviously due to the fact that most light came laterally in the space through side windows.

In conclusion, the study showed that the daylighting quality evaluation based on illuminance, distribution, glare and directivity proved to be useful in characterising lighting conditions in the rooms.

For the study of illuminance, the calculation of the UDI proved to be much more useful and precise than a simple analysis of DF. Considering DF alone may well lead to the selection of excessive glazing areas in buildings. This has been pointed out before by other researchers.[34] The DF optimised building admits as much daylight as possible into the building, following a 'the more the better' approach. Commercial buildings with fully glazed facades often exhibit comfort and energy problems. There is now a growing concern in the US that the DF basis of LEED is promoting the design and construction of buildings that are over-glazed, and that the cooling costs for these buildings are likely to outweigh whatever savings may result from daylighting.[34] In fact, providing too much daylight could well result in increased usage of electrical lighting as the blinds are likely to remain drawn much of the time.[12]

The study of luminance ratios was informative and provided quantitative proof that the colour selected for the furniture was too dark, which was also observed in reality.

However, the low DGP values obtained tend to confirm that the criteria used for the luminance ratios may be too strict for situations with daylight, which is supported by the recent literature. Finally, our assessment indicates that the Ev/Es ratios are very informative providing an additional insight into the flow of light in the space and must absolutely be included.

5.2. Limitations

The use of computer simulations to assess light quality instead of real participants is a major limitation of this study. In future work, it will be interesting to compare the computer-based assessment with subjective assessments in the real rooms. Another major limitation is the use of a series of clear skies instead of all-year meteorological data for most of the indicators used. The proposed methodology should be tested using full-year sky data combined with the daylight coefficient approach as made possible with DAYSIM. Another limitation of this study is the fact that the office rooms modelled did not have any electric lighting or shading devices, which is not realistic. A further step should consist of integrating both electric lighting, dimming strategy or control as well as a shading device in the simulations. Last but not least, the study only considered visual aspects and failed to account for the biological and emotional dimensions of lighting quality. Benchmark values related to the biological and emotional aspects are not yet well established by fundamental research and it is therefore impossible to evaluate a space or design according to relevant criteria.

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